

# Application of Geiger-mode photo sensors in Cherenkov detectors

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## Abstract

Silicon-based photosensors (SiPMs) working in the Geiger-mode represent an elegant solution for the readout of particle detectors working at low-light levels like Cherenkov detectors. Especially the insensitivity to magnetic fields makes this kind of sensors suitable for modern detector systems in subatomic physics which are usually employing magnets for momentum resolution. In our institute we are characterizing SiPMs of different manufacturers for selecting sensors and finding optimum operating conditions for given applications. Recently we designed and built a light concentrator prototype with  $8 \times 8$  cells to increase the active photon detection area of an  $8 \times 8$  SiPM (Hamamatsu MPPC S10931-100P) array. Monte Carlo studies, measurements of the collection efficiency, and tests with the MPPC were carried out. The status of these developments are presented.

*Keywords:*

Silicon photomultiplier, Light concentrator, position-sensitive photodetector matrix, Cherenkov detector

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## 1. Introduction

The position sensitive detection of Cherenkov light is extremely important for particle identification in many particle physics experiments like in the upcoming PANDA experiment [1] at FAIR. The challenge is the efficient detection of photons at low light levels with very good timing performance. The field of photon detection has experienced considerable progress with the development of matrix-APDs operated in the Geiger-mode. One accepted name of such a device is silicon photomultiplier (SiPM). SiPMs have high amplification in the order of  $10^6$  similar to traditional photomultipliers (PM). The main advantages are the rather high photo detection efficiency of some devices in the blue wavelength range (about twice compared to PMs), sub-nanosecond timing, compact and robust design. The insensitivity to even high magnetic fields is a major surplus in modern particle detectors which are usually employing magnetic fields. Typical applications of SiPMs studied at the Stefan Meyer Institute are the readout of scintillating fiber detectors [3] and timing detectors using the fast Cherenkov process [6]. There are attempts to construct arrays of SiPMs for RICH (see e.g. [5]). In order to select the SiPM type with the best performance in photon detection efficiency, dark count rate, and timing performance a study of the characteristics was performed [6]. For position sensitive devices the small format factor calls for the increase of the detection area with light concentrators like Winston cones, small lenses, or mirror-type

light concentrators. We are reporting on the development, Monte Carlo simulation, and test of a  $8 \times 8$  cell light concentrator and the measured characteristics of the selected SiPM type (Hamamatsu MPPC S10931-100P with  $3 \times 3$  mm<sup>2</sup> active area) which will be arranged in an  $8 \times 8$  matrix to be readout with integrated electronics.

## 2. Light concentrator

The function of a light concentrator is to enhance the number of photons reaching a detector above the number which is present without concentrator. In contrast to an imaging system, image conservation is not required. Many different and fairly complex systems have been proposed to optimize light concentration in various applications. Having however an application in a large high energy physics experiment in mind we considered a simple but robust and easy to fabricate solution.

The light concentrator consists of a plate of  $8.4 \times 8.4$  cm<sup>2</sup> containing 64 regularly arranged pyramid-shaped funnels with quadratic (rounded edges) entrance and exit apertures of  $7 \times 7$  mm<sup>2</sup> and  $3 \times 3$  mm<sup>2</sup>, respectively. It was designed to be combined with a SiPM array consisting of  $8 \times 8$  MPPCs with  $3 \times 3$  mm<sup>2</sup> active area. The concentrator is made out of brass and the funnels were produced by electroerosion. Afterward the plate was chrome-plated. A photograph is displayed in figure 1. The height of the concentrator plate (length of funnels) used for this study is 4.5 mm.

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Figure 1: Photograph of the light concentrator. The chrome-plated 4.5 mm thick brass plate contains 64 pyramid-shaped funnels with quadratic (rounded edges) entrance and exit apertures of  $7 \times 7 \text{ mm}^2$  and  $3 \times 3 \text{ mm}^2$ , respectively.

### 2.1. Monte Carlo Studies of the light concentration efficiency

In order to estimate the collection efficiency of the light concentrator and to study its dependence on the length of the funnels and the angle of incidence of the photons we carried out Monte Carlo simulations. Photons with given direction were produced at the entrance aperture and their path was followed until they were either absorbed by the funnel walls or left the funnel through either of the apertures. The collection efficiency  $\epsilon_{col}$  of a single funnel is defined by

$$\epsilon_{col} = \frac{n_d / N_{phot}}{(3/7)^2} \quad (1)$$

where  $n_d$  is the number of photons reaching the exit aperture and  $N_{phot}$  is the total number of simulated photons penetrating the entrance aperture (typically  $\approx 10^5$ ). If all photons entering the entrance aperture of a funnel were transported to the exit aperture a collection efficiency of  $(7/3)^2 = 5.4$  would result. The optical properties of the funnel walls were defined by a reflection coefficient and a factor characterizing the roughness of the surfaces. In figure 2 results are shown for the idealized case of specular reflection (neglecting absorption and assuming perfectly smooth surfaces). The points where the photons entered the funnel were distributed homogeneously over the entrance aperture. The such determined collection efficiency is drawn as function of angle of incidence  $\Theta$  (angle relative to the aperture normal) for different values of the funnel length  $h$ . In these simulations the azimuthal angle of the incident photons was kept constant and set to 0 degrees.

At normal incidence ( $\Theta = 0$  degrees) the collection efficiency increases with increasing funnel length and reaches

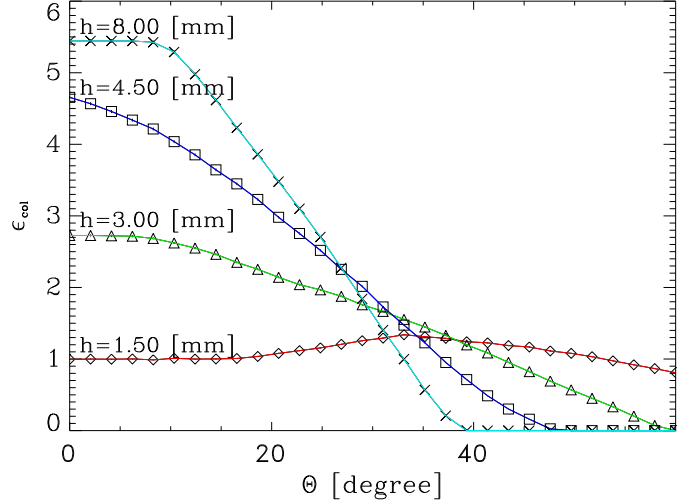


Figure 2: Light collection efficiency as function of angle of incidence  $\Theta$  (azimuthal angle of incidence is 0) for different values of the funnel length  $h$ . Specular reflection is assumed. The entrance points of the photons to the funnels was distributed homogeneously in the entrance aperture.

the optimum value of 5.4 at  $h > 6 \text{ cm}$ . At larger angles ( $\Theta > 30$  degrees) the collection efficiency is generally smaller than at normal incidence. However, here the relation between  $\epsilon_{col}$  and  $h$  changes, such that the collection efficiency is largest at small funnel length and decreases with increasing funnel length. Note, that since in these simulations the absorption of the photons in the funnel walls is neglected the only way for photons to escape from the funnel without reaching the exit aperture is to leave upwards through the entrance aperture. This happens to photons which enter the funnel close to a corner and are reflected from funnel wall to funnel wall and finally back to the entrance aperture.

The optimum choice of the height of this kind of light concentrator depends on the expected angular distribution of the incident light. To estimate the experimentally achievable collection efficiency, the true spatial and angular distribution of the incident photons must be known and the absorption of the photons on the walls of the funnels and also diffusive reflection need to be taken into account.

The effect of the absorption can be roughly estimated without repeating the simulations with modified optical properties of the funnel walls by multiplying the results shown in figure 2 with a factor  $f_{abs}^{n_{ref}}$ , where  $f_{abs}$  is the absorption coefficient of the funnel wall and  $n_{ref}$  is the number of reflections the photon experiences before it exits through the exit aperture.  $n_{ref}$  is a function of  $h$ , the angle of incidence, and the position the photon enters the funnel. In the simulated situation, the average number of reflections at a given  $\{h, \Theta\}$  pair is largest at large  $h$  and small  $\Theta$  and smallest at small  $h$  and large  $\Theta$ . Thus for a given light source, a geometry with large  $h$ , which seems best in the simulations without absorption, might turn out to be less efficient than a geometry with smaller  $h$ , when

taking absorption into account. The light concentrator we are experimenting with has a height of 4.5 mm. If we assume a reflection coefficient of 0.55 (Chromium at 400 nm [7]) we find from the simulations an average light collection efficiency of around 2.8 at normal incidence, which falls below 1 at  $\Theta > 30$  degrees (with an average value of 1.5 for  $0 < \Theta < 60$  degrees, case of uniformly distributed angles of incidence).

## 2.2. Measurement of the light concentration efficiency

In order to experimentally test the collection efficiency of the light collector we used two different settings.

The first setup is shown in figure 3. The light source was the squared end face of a plexiglas bar, which was illuminated from the other side with diffused light from a blue laser (408 nm). Along the long sides the plexiglas bar was wrapped into aluminum to enhance the internal reflection. With this a fairly homogeneous light source was provided with a presumably broad (although not well defined) angular distribution of the emitted photons. As photo sensor we used a  $3 \times 3 \text{ mm}^2$  MPPC (S10931) sensor from Hamamatsu. It was mounted opposite to the end face of the plexiglas bar in a distance of  $\approx 5 \text{ mm}$  with the sensitive surface facing the light source. The light concentrator was mounted on a sliding bar, between light source and MPPC. This allowed to move the light concentrator, remotely controlled, in and out of the path of the light without altering the relative position of light source and photo sensor. The in-position of the light concentrator was adjusted such that the exit aperture of one funnel exactly matched the sensitive area of the MPPC. The entire setup was mounted in a black box.

In a series of measurements we determined the signal height registered by the MPPC with the light concentrator in in- ( $s_{in}$ ) and out-position ( $s_{out}$ ) for different funnels. The collection efficiency  $\epsilon_{col}$  is computed with  $\epsilon_{col} = s_{in}/s_{out}$ . We found an average value of  $\epsilon_{col} \approx 1.8 \pm 0.2$ .

This is close to the value of 1.5 which is found by simulations for the case of homogeneously spatial distributed light and uniform distribution of the angle of incidence between 0 and 60 degrees assuming an reflection coefficient of the funnel walls of 0.55.

In the second setup, the light concentrator was irradiated with nearly parallel and normal incident light (estimated maximum  $\Theta$ -angle of 4 degrees). As photosensor a photodiode of  $10 \times 20 \text{ mm}^2$  active area was used. The light concentrator was covered with a blind leaving two funnel apertures open. The light throughput was measured once with the light illuminating the top face of the light concentrator ( $s_{top}$ ) and once from the bottom ( $s_{bottom}$ ).  $\epsilon_{col}$  is then obtained by the ratio of the two measurements  $\epsilon_{col} = s_{top}/s_{bottom}$ . For this setup we found  $\epsilon_{col} \approx 2.5$ . This is comparable with the factor 2.8 which results from simulations of normal incident light, assuming a reflection coefficient of 0.55 of the funnel walls. The results seem promising and justify further investigations.

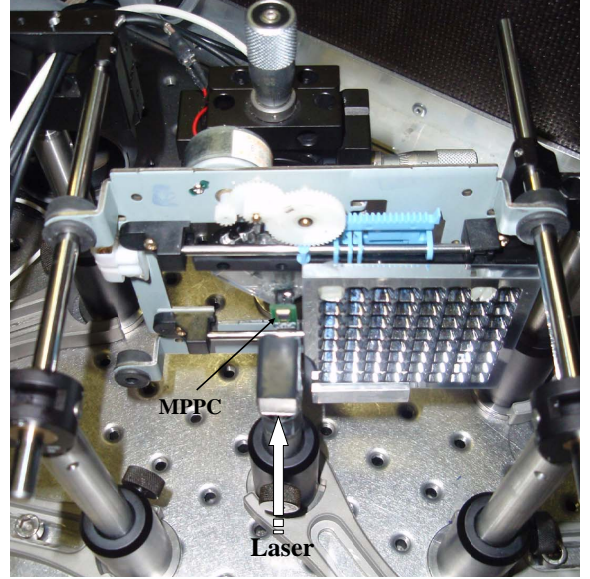


Figure 3: Photograph of the setup used to measure the collection efficiency of the light concentrator. A plexiglas bar which is illuminated with blue laser light serves as light source. An MPPC was used to measure the light intensity. The light concentrator is mounted on a sliding bar between light source and photo sensor.

## 3. Characterization of SiPMs for the readout array

As readout device for the light concentrator we consider to use the recent large active area SiPMs - the Multi-Pixel Photon Counters (MPPCs) from Hamamatsu [8]. These MPPC photo sensors are sensitive in the blue-light range ( $\approx 400 \text{ nm}$ ) which matches well with the light emitted by scintillators and Cherenkov radiators. From the series of MPPCs with an active area of  $3 \times 3 \text{ mm}^2$  we selected the type S10931-100P because of its large fill factor (78.5%) and the very small housing which allows for a compact arrangement of several devices in a matrix for readout of the entire light collector.

Besides the fact, that SiPM are resistant against magnetic fields, the most relevant performance figures of MPPCs in subatomic-physics applications is the dark count rate and the time resolution. Especially in cases where only few photons carry the physical information the ability to detect single photons is very appealing. This intrinsic ability of SiPMs can however be limited by large dark count rates. Fast timing e.g. allows for higher processing rates and more precise determination of physical quantities [2].

In view of a possible usage of these photo sensor for such applications we measured its dark count rate and timing performance as function of the temperature and over-voltage (difference between the applied bias voltage and the breakdown voltage). Here we present preliminary measurements taken at a temperature of  $-10^\circ\text{C}$ .

### 3.1. Dark count (noise) rate

The MPPCs are solid-state devices which generate noise due to thermal excitation [8]. The noise rate is measured

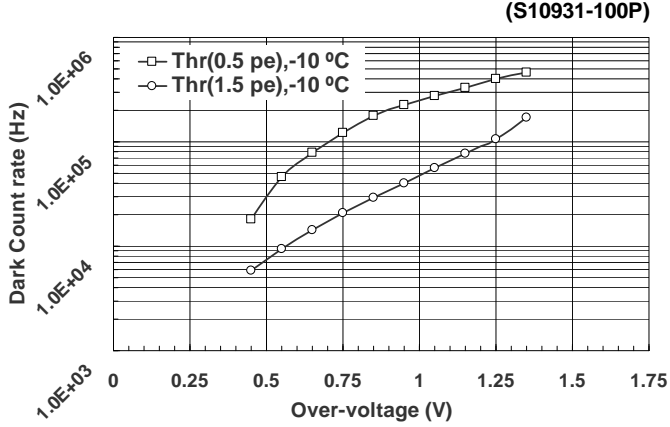


Figure 4: Dark count rate as a function of over-voltage, at  $-10^{\circ}\text{C}$ . Square and circular symbols correspond to data points at 0.5 p.e. and 1.5 p.e. thresholds levels, respectively.

by counting the number of output signals with an amplitude exceeding a given threshold value in absence of an external light input. Figure 4 shows the measured dark count rates at  $-10^{\circ}\text{C}$  and at different over-voltage values. The threshold level was adjusted to be 0.5 and 1.5 photoelectrons (p.e.).

At a threshold of 0.5 p.e. the dark count rate increases from around 20 kHz at an over-voltage of 0.5 V to approximately 0.5 MHz at 1.3 V over-voltage. The dark count rate drops rapidly with increasing threshold levels. By increasing the threshold to 1.5 p.e. the dark count rate is reduced by approximately a factor 3.

### 3.2. Timing performance

The time resolution of a SiPM depends on the operation conditions and the number of detected photons. Especially in applications with low light levels a proper selection of the operation temperature and voltage is essential to obtain good timing performance [4]. In order to measure the time resolution of the S10931-100P MPPC the device was stimulated with short light pulses from a blue laser. Amplitude and time of the response was recorded and the time resolution was determined by the standard deviation of the recorded response time. In order to obtain the time resolution as function of number of fired pixels (NFP) the measured amplitude distribution was split into narrow bins, corresponding to 1-2 fired pixels, and the time resolution was determined separately for each bin. A detailed description of the experimental setup and methods is given in [4].

The results of these measurements are summarized in figure 5. The time resolution is plotted as NFP for different values of over-voltage at a temperature of  $-10^{\circ}\text{C}$ . In the insets the gain and dark current are displayed as function of over-voltage.

The dependence of the time resolution on the over-voltage and NFP is similar to what we found for the S10362-

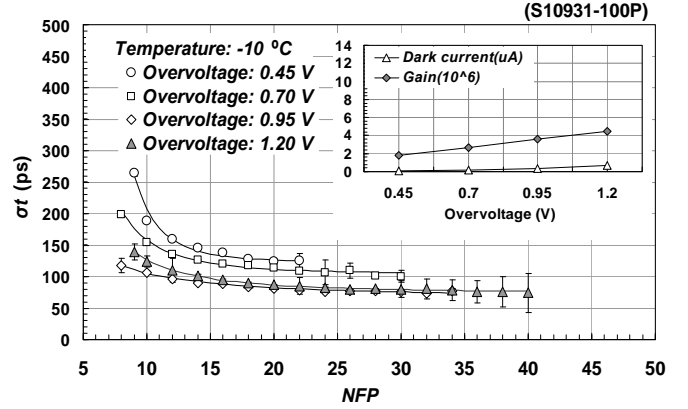


Figure 5: Time resolution as function of number of fired pixels (NFP) of the MPPC S10931-100P at  $-10^{\circ}\text{C}$ , and with different over-voltages. The insets show gain and dark current as function of over-voltage.

33-100C MPPC [4]. Especially at small NFP an appropriate selection of the operation conditions is necessary to obtain good timing performance.

## 4. Outlook

The characterization of the light concentrator and photo sensor as presented here, is the first step in a program which aims at the development of an efficient and compact detector for the readout of RICH and DIRC detectors. Further work is needed to study and optimize the collection efficiency (e.g. replace chrome-plating by plating with better reflectivity) of the light concentrator. Integration of 64 MPPCs into a matrix with the corresponding front-end electronics is an additional task.

## 5. Acknowledgments

This work is partly supported by INTAS (project 05-1000008-8114) and Hadronphysics2 (project 227431). One of us (G.A.) acknowledges the support by the Egyptian Ministry of higher education.

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